Predictability of Particle Trajectories in the Ocean

Tamay M. Özgökmen
Division of Meteorology and Physical Oceanography
Rosenstiel School of Marine and Atmospheric Science
4600 Rickenbacker Causeway
Miami, Florida 33149
phone: 305 421 4053, fax: 305 421 4696, email: tozgokmen@rsmas.miami.edu

Annalisa Griffa
phone: 305 421 4816, fax: 305 421 4696, email: agriffa@rsmas.miami.edu

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LONG-TERM GOALS

The long term goal of this project is to determine optimal sampling strategies for drifting observing systems, such as buoys and gliders, in order to enhance prediction of particle motion in the ocean, with potential applications to ecological, search and rescue, floating mine problems, and design of real-time observing systems.

OBJECTIVES

Our main objective is to develop Lagrangian techniques to improve our fundamental understanding of turbulent transport phenomena in the ocean. The objectives of the project serve the ONR thrust area of adaptive sampling and Lagrangian tracing. Another aspect of the research focuses on a better understanding of the nature of mesoscale and sub-mesoscale turbulent processes, which is relevant to ONR thrust area on sub-mesoscale variability associated with fronts, turbulence and mixing.

APPROACH

The work is based primarily on the analysis of output from coastal and ocean circulation models, as well as data from drifters and VHF radars deployed for real-time experiments. We also develop and/or employ Lagrangian models and techniques as needed.

WORK COMPLETED

1) Analysis of the relative dispersion characteristics as a function of spatial scale using finite-scale Lyapunov exponents (FSLEs) from a hierarchy of ocean models, namely a two-dimensional turbulence model, large-scale ocean model (HYCOM) and idealized, buoyancy driven flows using ROMS (Poje et al., 2009, paper in press).

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2) Quantification of transport properties in a small-scale coastal flow using VHF radar measurements and two clusters of surface drifters (Haza et al., submitted to Lim. Ocean.).

3) Participation in the 2008 REA (Rapid Environmental Assessment) trials organized by NURC/NATO (led by A. Alvarez and M. Rixen) and NRL (led by E. Coelho). Our main role was to compute 3D FSLEs in two nested domains of NCOM in order help guide the three gliders used in the experiment.

4) Organization of the fourth LAPCOD (Lagrangian Analysis and Prediction of Coastal and Ocean Dynamics) meeting in France during 7-11 September, 2009:

http://www.rsmas.miami.edu/LAPCOD/2009-La_Londe-les-Maures/

This meeting was attended by some 60 international and interdisciplinary scientists.

RESULTS

1) Relative dispersion from a hierarchy of ocean models:

In order to determine the effect of Eulerian spatial resolution on the two particle statistics of synthetic drifter trajectories, we examine a hierarchy of ocean models, starting from 2D turbulence simulations, progressing to idealized simulations of a buoyant coastal jet with ROMS, and finally to realistic HYCOM simulations of the Gulf Stream. In each case, particle dispersion at large time and space scales is found to be controlled by energetic meso-scale features of the flow that are relatively insensitive to the resolution of finer scale motions. In all cases, time-distance graphs given in terms of computed Finite Scale Lyapunov Exponents show an expected increase in the extent of exponential scaling with increasing spatial smoothing of the velocity field. The limiting value of the FSLE at small separation distances is found to scale remarkably well with the resolution of Eulerian velocity gradients as given by the average of positive Okubo-Weiss parameter values.

The motivations leading to this study were covered to a large extent in our 2008 report, and this study is now close to publication (Poje et al., 2009, available from the Ocean Modelling website). Therefore, we do not devote further discussions to this issue.

2) Transport properties in the Gulf of La Spazia from VHF radar and surface drifters:

Surface transport characteristics in the Gulf of La Spezia, which is a small-scale feature along the western Italian coast, are explored using the VHF radar observations collected in the context of POET-LASIE experiment for two weeks in the summer of 2007. In addition, an independent data set from two clusters of CODE type surface drifters are employed.

This small scale coastal flow from VHF radar indicates a complex Lagrangian Coherent Structures (LCS) estimated using the FSLE. We find that there is a very good agreement with the spatial and temporal evolution of the FSLE fields and the motion of the drifter clusters (Fig. 1). In particular, the drifters follow but do not cross the FSLE ridges, this confirming that the FSLE ridges acts as natural transport barriers in the flow field. The FSLE seems to be an effective tool in mapping the natural transport barriers of the flow field, even in the presence of rapidly varying coastal flow with no apparent coherent structures.

The surface flow in the Gulf of La Spezia appears to be mainly forced by the ambient circulation in the Ligurian Sea, which sets the large scale deformation field. We also find some evidence of strong modulation of the surface current by the local wind forcing at diurnal and semi-diurnal frequencies.. The wave number spectrum is limited by the small size of the domain (5 to 10 km) and radar resolution (250 m). The spectrum shows peaks of energy in the mesoscale range, 1 km. Nevertheless, the Rossby number is large enough Ro $\approx$ 1 for rotational effects to be small. The wave number spectrum is highly time dependent. Overall, isolated coherent structures that are characteristic of geostrophic turbulence, and their breakdown into smaller scale eddies are not observed. It is found that the FSLE is nearly scale independent for the spatial scale range of 0.1125 m to 1-2 km, varying within a narrow regime of 5 day^{-1} and 7 day^{-1}. Since the observational area of the radar essentially corresponds to the sub-meso-scale range, the relative dispersion in the mesoscale range and beyond is not quantified (Fig. 2). Computation of $D^2(t)$ supports this exponential or non-local regime, and value obtained on the basis of the FSLE. Therefore, there are no indications of significant control by rapidly-evolving, small-scale turbulent features on the relative dispersion. As shown in Fig. 3, the FSLE value of 5 day^{-1} is more than an order of magnitude larger those found from modeling results by Haza et al. (2008) and Poje et al. (2009) and the observational value obtained by LaCasce and Ohlmann (2003) based on SCULP data in the Gulf of Mexico, but somewhat smaller than the limiting value put forward by Lumpkin and Ellipot (2009) from CLIMODE drifters in the Gulf Stream. We also find that scaling the limiting value of the FSLE by the resolved gradients of the Eulerian fields as given by a positive Okubo-Weiss criterion is useful, and the linear fit to data from Poje et al. (2009) almost extends to the flows considered here.

The horizontal flow convergence is seen to have a small yet tangible effect on relative dispersion in this study. Nevertheless, given that the radar resolution of 250 m is at the high end of persistent phenomena such as Lingmuir cells, and our the relative dispersion study relies on synthetic rather than real drifters, we are unable to address this matter further at this stage.

Regarding future studies, the combination coastal VHF radars and surface drifters appears to provide independent and complementary data sets which seem extremely useful to explore transport processes at the sub-meso-scale range. Given the recent proliferation of VHF radars and reduction in cost of surface drifters with GPS sampling, similar studies should be pursued at different geographical locations to order to develop a better understanding of the nature of coastal transport. Second, with the sampling of smaller scales along the coastal ocean with complex bathymetry, shallow waters and wind forcing, the effect of horizontal flow divergence on relative dispersion deserves more attention. In particular, the implications of using 2-D drifters in a flow that may show 3-D patterns needs to be investigated.

3) Three-dimensional FSLEs and glider data from 2008 REA:

We have participated in 2008 Real time Environmental Assessment (REA) trials organized by NURC/NATO (led by A. Alvarez and M. Rixen) and NRL (led by E. Coelho). We have supplied 3D FSLEs in two nested domains of NCOM on a daily basis for about 6 weeks in order help guide the three gliders used in the experiment. To our knowledge, this is the first time when 3D FSLEs have been employed in an operation program. An example of the fields supplied is shown in Fig. 4a. We have started to do some post-analysis as well (Fig. 4b.c). Overall, NCOM shows a good agreement

with glider fields for temperature but large discrepancies are obtained for the velocity and salinity field.

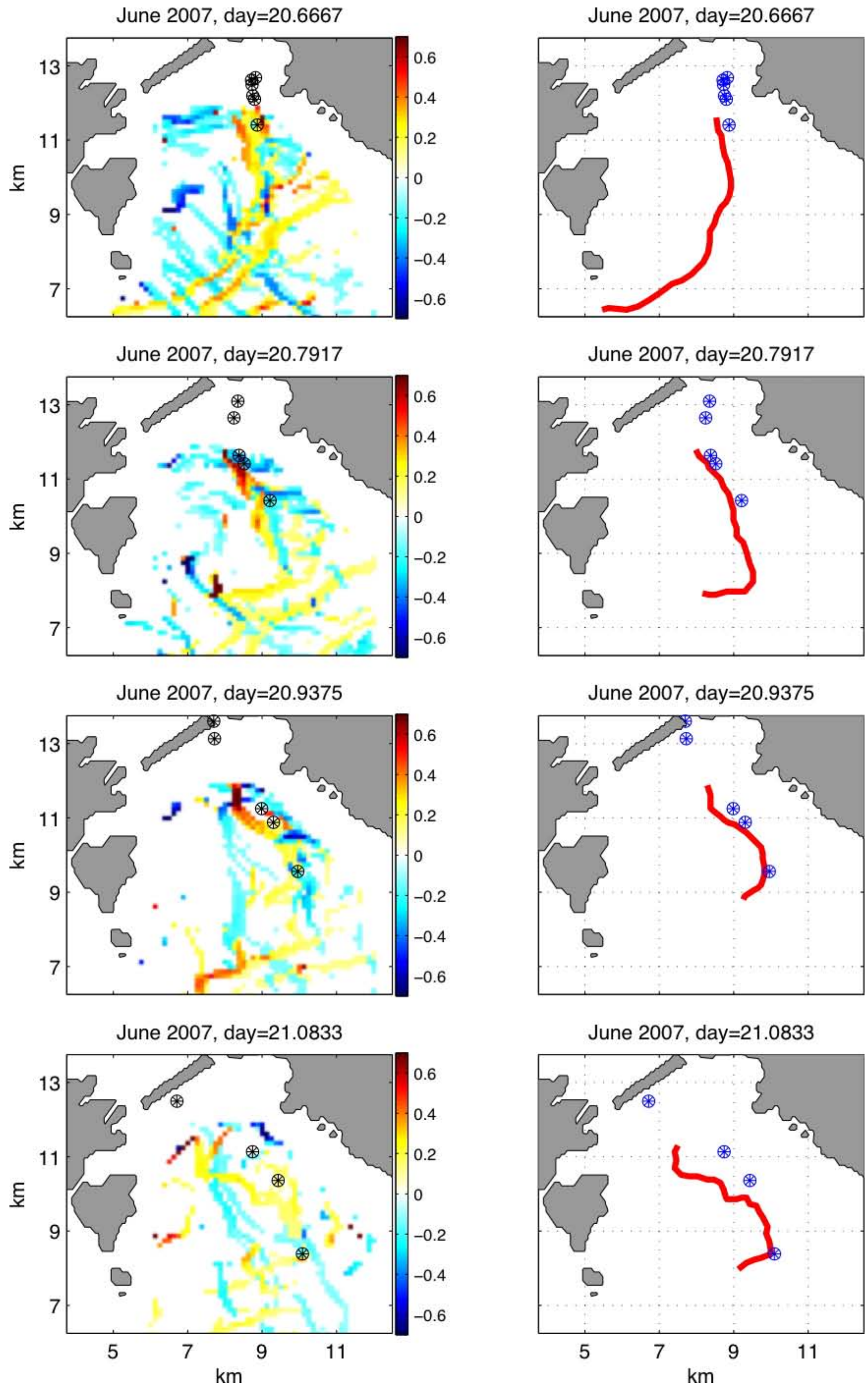

Fig. 1: (Left panel) Spatial distribution of FSLEs (in days^{-1}) computed forward in time (positive) and backward in time (negative) on the basis of VHF radar derived velocity fields in the Gulf of La Spezia. Superimposed is the independent data set, namely the observed drifters in Cluster-1. (Right panel) The main FSLE ridges that appear to be controlling the drifter trajectories.

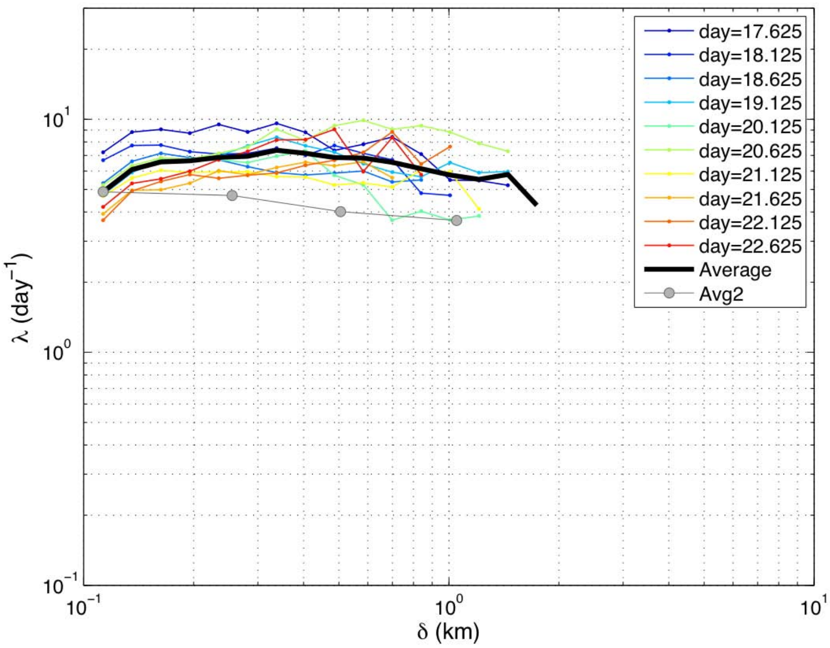

Fig. 2: Spatial dependence of FSLEs from Lagrangian particle releases at 10 subsequent periods (colored curves) and their average (thick solid curve) using chance pairs. The gray line shows the same calculation on the basis of original pairs. Note the flat/exponential regime, indicating that relative dispersion is non-local, namely controlled by the large scale straining field rather than by small scale turbulent features.

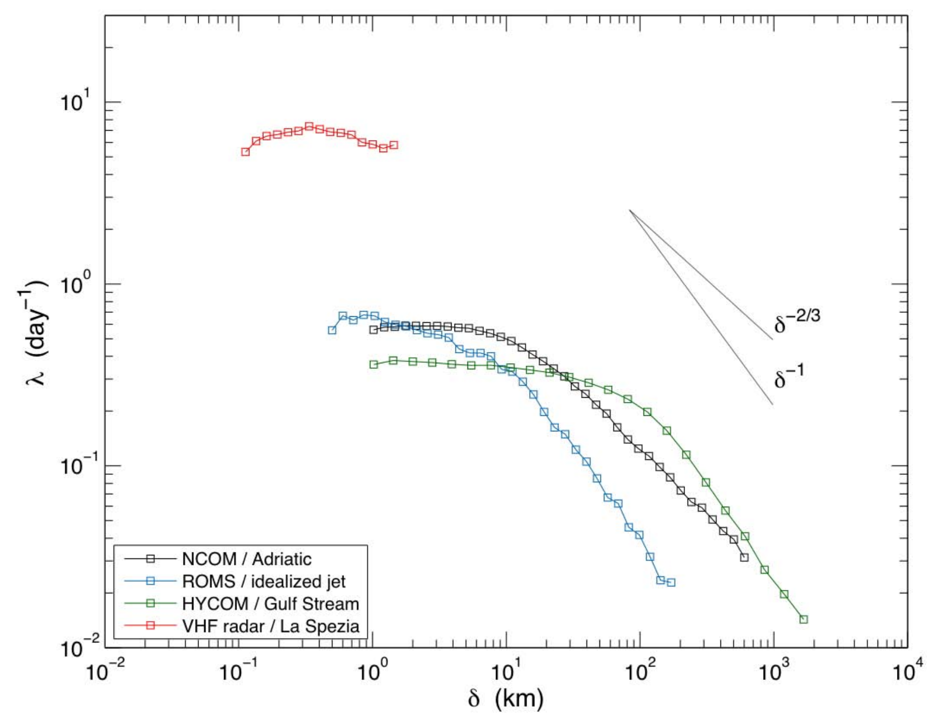

Fig. 3: FSLE curves from the VHF radar study, as well as those obtained on the basis of models presented in Poje et al. (2009, HYCOM and ROMS) and Haza et al. (2008, NCOM).

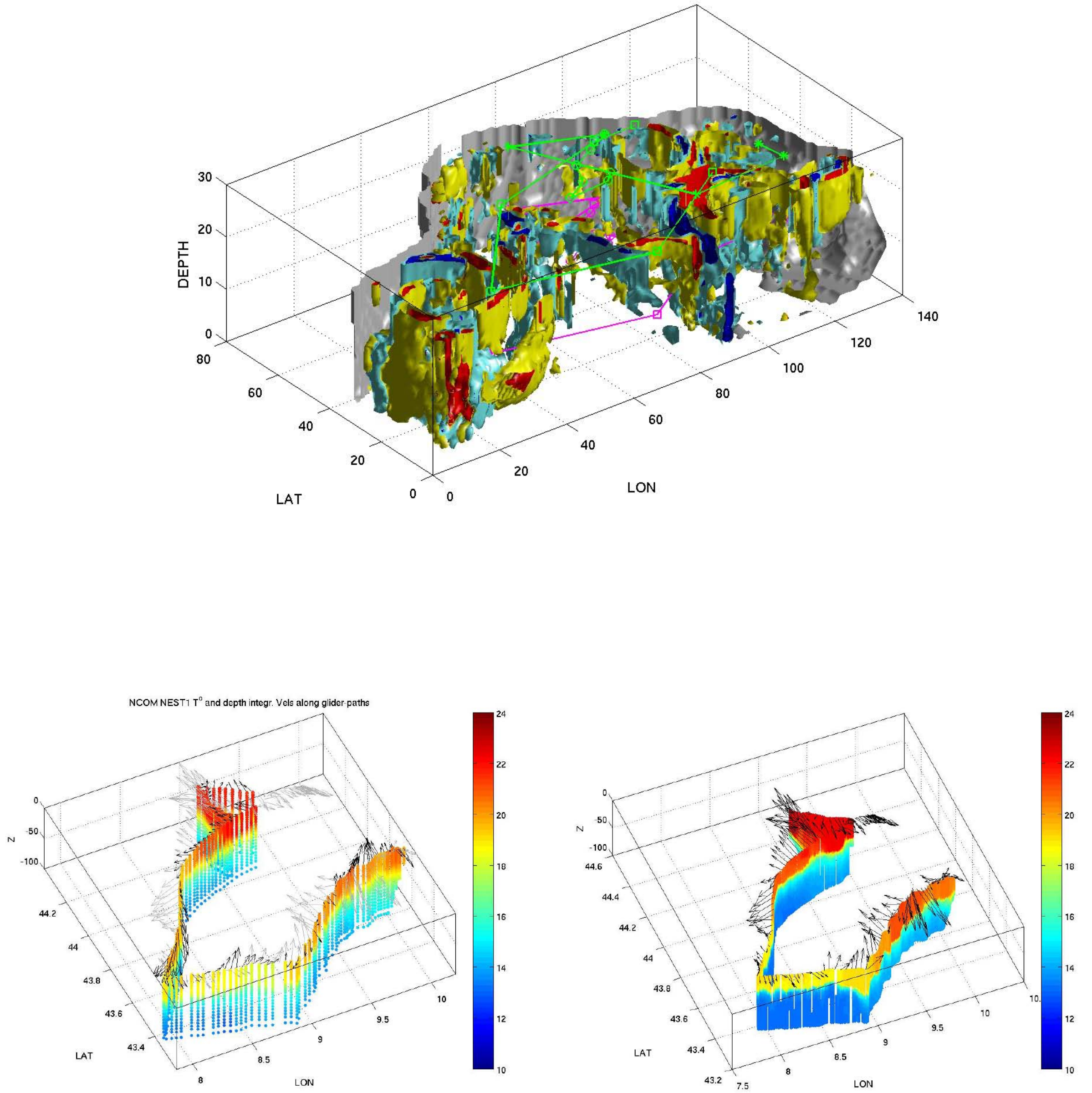

Fig. 4: (Upper panel) Three-dimensional FSLE surfaces computed from NCOM output in the Ligurian Sea in the vicinity of glider paths, shown in green and pink lines. (Lower left) Depth averaged velocity vectors and salinity profiles from NCOM along the path of one of the gliders. (Lower right) Same as the previous figure but directly from the glider.

IMPACT/APPLICATIONS

The investigation of the predictability of particle motion is an important area of study, with a number of potential practical applications at very different scales, including searching for persons or valuable objects lost at sea, tracking floating mines, ecological problems such as the spreading of pollutants or fish larvae, design of observing systems and navigation algorithms.

RELATED PROJECTS

Lagrangian Turbulence and Transport in Semi-Enclosed Basins and Coastal Regions, PI: A. Griffa, N00014-05-1-0094.

Statistical and Stochastic Problems in Ocean Modeling and Prediction, PI: L. Piterbarg, N00014-99-1-0042.

Optimal Deployment of Drifting Acoustic Sensors: Sensitivity of Lagrangian Boundaries to Model Uncertainty, PI: A. Poje, N00014-04-1-0192.

PUBLICATIONS (2008-2009)

Haza, A., A.C. Poje, T.M. Özgökmen, P. Martin, 2008: Relative dispersion from a high-resolution coastal model of the Adriatic Sea. Ocean Modelling, 22, 48-65 [published, refereed].

Magaldi, M., T.M. Özgökmen, A. Griffa, E. Chassignet, M. Iskandarani and H. Peters, 2008: Turbulent flow regimes behind a coastal cape in a stratified and rotating environment. Ocean Modelling, 25, 65-82 [published, refereed].

Poje, A.C., A.C. Haza, T.M. Özgökmen, M. Magaldi and Z.D. Garraffo, 2009: Resolution dependent relative dispersion statistics in a hierarchy of ocean models. Ocean Modelling [in press, refereed].

Magaldi, M., T.M. Özgökmen, A. Griffa and M. Rixen, 2009: On the response of a turbulent buoyant current to wind events. Ocean Dynamics [in revision, refereed].

Haza, A.C., T.M. Özgökmen, A. Griffa, A. Molcard, P.M. Poulain and G. Peggion, 2009: Transport properties in small scale coastal flows: relative dispersion from VHF radar measurements in the Gulf of La Spezia. Lim. Ocean. [submitted, refereed].